

5           **MIXER HAVING LOW NOISE, CONTROLLABLE GAIN, AND/OR LOW  
              SUPPLY VOLTAGE OPERATION**

**TECHNICAL FIELD OF THE INVENTION**

10           This invention relates generally to radio frequency  
             (RF) technologies and more particularly to mixers used  
             within such RF technologies.

**BACKGROUND OF THE INVENTION**

15           Wireless communication systems are known to enable one  
             wireless communication device to transmit data to at least  
             one other wireless communication device via a wireless  
             transmission medium. Such wireless communication systems  
20           may range from National or International cellular telephone  
             systems to point-to-point in-home networking. For  
             instance, a wireless communication system may be  
             constructed, and hence operates, in accordance with one or  
             more standards including, but not limited to, IEEE 802.11a,  
25           IEEE 802.11b, Bluetooth, advanced mobile phone services  
             (AMPS), digital AMPS, global system for mobile  
             communications (GSM), code division multiple access (CDMA),  
             wireless application protocol (WAP), local multi-point  
             distribution services (LMDS), multi-channel multi-point  
30           distribution systems (MMDS), and/or variations thereof.

             As is also known, such wireless communication systems  
             use radio frequencies for the wireless transmission medium.  
             Thus, each wireless communication device that transmits  
35           data requires an RF transmitter and each wireless

communication device that receives data requires an RF receiver. In general, an RF transmitter includes a modulator, local oscillator, one or mixers, power amplifier and an antenna. The inter-operation of these components is well known to modulate a data signal into an RF signal. Correspondingly, an RF receiver includes an antenna, which may be shared with the RF transmitter, a low noise amplifier, a local oscillator, one or more mixers, a summing module, filtering, and a demodulator to recapture the data signal from the RF signal.

Consequently, each wireless communication device includes a plurality of mixers within the RF transmitter and RF receiver to properly function within any type of wireless communication system. Not surprisingly, the quality of performance of a wireless communication device is dependent on the quality of performance (e.g., linearity) of the mixers included therein. A high quality mixer for certain applications is illustrated in Figure 1 and is known as the Gilbert mixer. The Gilbert mixer, as shown, may be implemented using standard CMOS technology, however, for low supply voltage applications (e.g., less than 3.3 volts), it is difficult to obtain sufficient gain due to the output resistors R0 and R1.

To overcome this limitation, the Gilbert mixer can be modified as shown in Figure 2. While this configuration improves the headroom capabilities of the mixer, it still has some limitations. For instance, such a mixer lacks built-in gain control, which would allow the gain of the mixer to be adjusted for various applications. In addition, the mixer, when used to directly translate RF

signals into base-band signals, includes a significant amount of flicker noise, which is produced by switching transistors MG1-MG4. Further, the voltage excursion on switching transistors MG1-MG4 may be quite large, which  
5 causes device reliability issues of the switching transistors. Still further, the maximum swing of the mixer output, while maintaining acceptable distortion performance, could be quite limited for low supply voltage applications (e.g., less than 2 volts).

10 Therefore, a need exists for a mixer that reliably operates at low voltages (e.g., less than 2 volts), provides gain adjustments, reduces adverse affects of flicker-noise and/or limits voltage excursions of its  
15 switching transistors, which improves device reliability.

#### BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure 1 illustrates a schematic block diagram of a prior art mixer;

Figure 2 illustrates a schematic block diagram of an alternate prior art mixer;

25 Figure 3 illustrates a schematic block diagram of a mixer in accordance with the present invention;

Figure 4 illustrates a schematic block diagram of an alternate mixer in accordance with the present invention;

30 Figure 5 illustrates a schematic block diagram of another mixer in accordance with the present invention;

Figure 6 illustrates a schematic block diagram of a further mixer in accordance with the present invention;

5        Figure 7 illustrates a schematic block diagram of a still further mixer in accordance with the present invention;

10       Figure 8 illustrates a schematic block diagram of a programmable gain RF transconductance section that may be incorporated in one or more of the mixers of Figures 3 through 7;

15       Figure 9 illustrates a schematic block diagram of an alternate programmable gain RF transconductance section that may be incorporated in one or more of the mixers of Figures 3 through 7;

20       Figure 10 illustrates a schematic block diagram of yet another mixer in accordance with the present invention;

Figure 11 illustrates a schematic block diagram of yet a further mixer in accordance with the present invention;

25       Figure 12 illustrates yet another embodiment of a mixer in accordance with the present invention; and

30       Figure 13 illustrates a schematic block diagram of an intermediate frequency module in accordance with the present invention.

#### DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Figure 3 illustrates a schematic block diagram of a mixer 10 that includes a reference current source 12, a programmable gain RF transconductance section 14, and switching quad transistors 16. The reference current source 12 is operably coupled to provide a reference current 28 to the programmable gain RF transconductance section 14. The programmable gain RF transconductance section 14, which will be described in greater detail with reference to Figures 8 and 9, receives a RF signal 18 and a gain setting signal 22. Based on these inputs and the reference current 28, the programmable gain RF transconductance section 14 produces an RF current 24. Accordingly, the RF current 24 is representative of the RF signal 18 amplified in accordance with the gain setting signal 22.

The switching quad transistors 16 are operably coupled to generate a frequency translated current 26 from a local oscillation voltage 20 and the RF current 24. Accordingly, the frequency translated current 26 represents an up-conversion of the RF current 24 with respect to the local oscillation voltage 20 and a down-conversion of the RF current 24 with respect to the local oscillation voltage 20. For example, if the RF current 24 is represented by  $\sin(\omega_{RF}t)$  and the local oscillation voltage 20 is represented by  $\sin(\omega_{LO}t)$ , the frequency translated current 26 would essentially equal  $\frac{1}{2} \cos(\omega_{RF} - \omega_L)t - \frac{1}{2} \cos(\omega_{RF} + \omega_L)t$ . Accordingly, the cosine component including the differences between the frequency represents the down-conversion and the cosine portion including the summation of the frequencies represent the up-conversion.

The switching quad transistors 16 may be implemented utilizing native transistors or non-native transistors. Such non-native transistors have a gate-to-source voltage threshold that is greater than 0 volts and is typically in the range of 0.4 volts to 0.7 volts. A native transistor has a gate to source voltage threshold of approximately 0 volts. By utilizing the native transistors, which have a larger minimum channel length than non-native transistors, within the switching quad transistor 16, flicker-noise is reduced in comparison to using non-native transistors. In addition, by utilizing native devices within the switching quad transistors, the maximum voltage experienced by the gate body junction of the switching quad transistors is reduced by almost 1 voltage threshold. Accordingly, this helps the reliability of the switching devices.

Figure 4 illustrates a mixer 30 that includes the reference current source 12, the programmable gain RF transconductance section 14, the switching quad transistors 16, a resistor section 36, a current source pair 34, and a common mode circuit 32. In this configuration, the switching quad transistor 16, the programmable gain RF transconductance section 14, and the reference current source 12 operate as previously discussed with reference to Figure 3.

The current source pair 34 is operably coupled to provide a DC current 38 to the switching quad transistors. The resistor section 36 is operably coupled to provide a current-to-voltage translation and to provide a common mode reference for common mode circuit 32. The common mode

circuit 32 provides a gate voltage to the current source pair 34 to regulate the DC current 38 at a desired level.

In this implementation, mixer 30 provides a mixed  
 5 voltage output of  $IF_n$  and  $IF_p$ , which results from the  
 current-to-voltage translation provided by the resistor  
 section 36. Also, in this configuration, the mixer  
 provides a low noise and gain controllable mixer that can  
 operate at low voltage supplies (e.g., approximately 2  
 10 volts).

Figure 5 illustrates a schematic block diagram of a  
 mixer 40 that includes the reference current source 12, the  
 programmable gain RF transconductance section 14, the  
 15 switching quad transistor 16 and a resistor section 42. In  
 this configuration, the frequency translated current 26 is  
 directly converted to a voltage via the resistor section  
 42.

20 As one of average skill in the art will appreciate,  
 the mixer 40 of Figure 5 provides controllable gain and low  
 noise operation, especially when the switching quad  
 transistors are implemented utilizing native transistors.  
 However, in comparison with the mixer of Figure 4, mixer 40  
 25 requires a slightly larger operating voltage.

Figure 6 illustrates a mixer 50 that includes  
 reference current source 12, the programmable gain RF  
 transconductance section 14, the switching quad transistors  
 30 16, current source pair 34, a common mode circuit 52, and a  
 bias circuit 54. The bias circuit 54 is operably coupled  
 to the current source pair 34 to provide gate voltage to

the current source pair enabling it to produce the DC current 38.

The common mode circuit 52 includes a resistor divider 58, an operational amplifier 56, transistor pair 60, and resistor pair 62. The resistor divider 58 is operably coupled to the switching quad transistors 16. The tap of the resistor divider 58 provides a common mode reference to the operational amplifier 56. The other input of the operational amplifier is coupled to a reference voltage. Accordingly, the common mode circuit 52 will regulate the common mode of the frequency translated current 26 with respect to the reference voltage provided to the input of the operational amplifier 56. The operational amplifier 56 drives the transistor pair 60 to produce a current that is provided to the resistor pair 62. The interconnection between the transistor pair 60 and resistor pair 62 provides the mixer output 64.

As one of average skill in the art will appreciate, by utilizing the common mode circuit 52 in conjunction with the other components illustrated in Figure 6, the supply voltage may be further decreased thus allowing mixer 50 to have a high quality of performance at very low supply voltages (e.g., approximately 1 volt to 1.8 volts). As one of average skill in the art will further appreciate, the common mode circuit 52 provides a folded cascoded output, which reduces voltage excursions of the transistor pair 60 thereby significantly improving supply voltage headroom at the mixer output 64. As one of average skill in the art will still further appreciate, the common mode voltage of the frequency translated current 26 is now an intermediate



node within the mixer, hence the common mode of the frequency translated current 26 is controlled, which reduces voltage swings on the drain side of the transistor pair 60. This further improves lower voltage operation of the mixer. As one of average skill in the art will also appreciate, the programmable gain RF transconductance section 14 allows the mixer to have controllable gain while the switching quad transistor 16, especially when implemented with native transistors, reduces noise of the mixer.

Figure 7 illustrates another mixer 70 that includes the reference current source 12, the programmable gain RF transconductance section 14, the switching quad transistor 16, the bias circuit 54, the current source pair 34, and a common mode circuit 72. The operation of the bias circuit 54, the current source pair 34, the switching quad transistor 16, the programmable gain RF transconductance section 14 and the reference current source 12 are as previously discussed.

The common mode circuit 72 includes the resistor divider 58, transistor pair 60 and resistor pair 62 of the common mode circuit 52 of Figure 6. The common mode circuit 72 further includes a 2<sup>nd</sup> resistor divider that includes resistors 74 and 76. The 2<sup>nd</sup> resistor divider 74 and 76 allow the reference voltage into operational amplifier 56 to be reduced. By reducing the reference voltage, the operational amplifier 56 has its output range at approximately 7/10ths of a volt. This enables the operational amplifier to be implemented utilizing a single stage N-input or P-input operational amplifier and meet the

constringent headroom constraints. Accordingly, the reference voltage may be set to approximately 1.4 volts.

Figure 8 illustrates a schematic block diagram of an embodiment of the programmable gain RF transconductance section 14 that includes a RF input transistor pair 82, a 1<sup>st</sup> inductor L1, a 2<sup>nd</sup> inductor L2, and a selectable transistor section 80. As shown, the RF input transistor pair 82 includes a pair of N-channel transistors operably coupled to receive the RF signal 18. The inductors L1 and L2 each include a tap that is operably coupled to the selectable transistor section 80. The selectable transistor section 80 includes three N-channel transistors.

The gain setting signal 22 is coupled to the gates of the transistors of the selectable transistor section 80. When the gain setting signal 22 is in a low-gain state, the center transistor, which is coupled to the node coupling L1 and L2, is active while the other two transistors are inactive. As such, the reference current 28 is based on the transconductance produced via the RF input transistor pair 82 and the full inductance of inductors L1 and L2.

When the gain setting signal is in a high-gain state, the outside transistors of the selectable transistor section 80 are enabled. This couples the taps of inductors L1 and L2 to produce the reference current 28. As such, the gain of the transconductance section 14 is increased since the inductance provided by L1 and L2 is reduced in comparison the low-gain state operation.

Figure 9 illustrates a schematic block diagram of an alternate embodiment of the programmable gain RF transconductance section 14. The transconductance section 14 includes the RF input transistor pair 82, a differential tapped inductor L3 and the selectable transistor section 80. The functionality of the RF input transistor pair 82 and the selectable transistor section 80 are as previously discussed with reference to Figure 8.

The differential tapped inductor L3 is a differential inductor that has each section tapped as illustrated. Accordingly, when the gain setting signal 22 is in a low-gain state, the center transistor of the selectable transistor section 80 is activated thus, employing the full inductance of both sections of the differential tapped inductor. When the gain setting signal 22 is in a high-gain state, the outside transistors of the selectable transistor section 80 are active thus, only a portion of the inductance of L3 is utilized.

As one of average skill in the art will appreciate, resistor dividers may be used within the transconductance section instead of the inductors to provide selectable gain, additional inductors may be used to provide further granularity of gain settings, or a combination thereof may be utilized. Regardless of the specific implementation used, the transconductance section 14 may be programmed to adjust the gain of the mixer for various mixing applications thus, enhancing the performance of such a mixer over a wide range of mixing applications.

Figure 10 illustrates a schematic block diagram of mixer 90 that includes switching quad native transistors 92, a RF transconductance section 94, and a reference current source 12. As configured, the reference current source 12 produces a reference current 28 that is provided to the RF transconductance section 94. The RF transconductance section 94 generates a RF current 24 from a RF signal 18 based on the reference current 28.

The switching quad native transistors 92, which each include native transistors, convert the RF current 24 into a frequency translated current 26 based on a local oscillation voltage 20. The native transistors utilized within the switching quad native transistors 92 reduce the flicker-noise injected by the mixer thereby increasing the performance capabilities of such a mixer.

Figure 11 illustrates a mixer 100 that includes the current source pair 34, common mode circuits 52 or 72, the switching quad native transistors 92, the RF transconductance section 94, and the reference current source 12. The RF transconductance section 94 includes a pair of transistors operably coupled to receive the RF signal 18 and a pair of inductors. The inductors improve the linearity of the RF transconductance section 94 but reduce the gain of the mixer. Alternatively, resistors may replace the inductors when headroom of the supply voltage is a less critical issue.

The overall function of mixer 100 is in accordance with the functioning of the mixers previously described. In particular, the RF transconductance section 94 converts

an RF signal 18 into an RF current 26. The switching quad native transistors 92 convert the RF current into a frequency translated current 26 based on a local oscillation voltage 20. The common mode circuit 52 or 72 provides a common mode reference point to produce the mixer output 64. To facilitate the generation of the frequency translated current 26; the current source pair 34 provides a DC current 38. Alternatively, resistors may replace the current source pair 34 if headroom of the supply voltage is a less critical issue.

Figure 12 illustrates a schematic block diagram of yet another mixer 110 that includes the reference current source 12, the RF transconductance section 94, switching quad transistor 16, common mode circuits 52 or 72 and current source pair 34. The functionality of mixer 110 is similar to the functionality of mixer 100 except that the switching quad native transistors 92 of mixer 100 have been replaced with non-native transistors within switching quad transistors 16.

Figure 13 illustrates a schematic block diagram of an intermediate frequency module 120 that includes a 1<sup>st</sup> mixer 124, a 2<sup>nd</sup> mixer 126, a local oscillator 122, a summing module 128 and a filter module 130. The IF module 120 may be used in a radio frequency receiver and/or in a radio frequency transmitter.

In operation, the 1<sup>st</sup> mixer 24 receives an in-phase component of an input signal (32) (e.g., an RF signal for a receive and an IF signal for a transmitter) and an in-phase component of local oscillation voltage 20. The 1<sup>st</sup> mixer

124, which may be any of the mixers illustrated in Figures 3-12, mixes the in-phase input signal and in-phase local oscillation to produce an I product 134. Similarly, the 2<sup>nd</sup> mixer 126 mixes a quadrature portion of the input signal 132 with a quadrature component of the local oscillation voltage 20 to produce a quadrature product 136. Each of the I and Q products 134 and 136 will include an up-conversion of the input signal based on the local oscillation voltage 20 and a down-conversion of the input signal based on the local oscillation voltage 20.

The summing module 128 sums the I product 134 and the Q product 136 to produce a summed signal 138. The filtering module 130 filters either the up-converted portion of the summed signal 138 or the down-conversion portion of the summed signal 138 to produce an IF signal 140. The filtering module 130 will filter the down-conversion portion of the summed signal 138 such that the up-conversion portion is left when the IF module 120 is incorporated in a radio transmitter. Conversely, the filtering module 130 will filter the up-conversion portion of the summed signal 138 and thus pass the down-conversion portion of the summed signal 138 when the IF module 120 is incorporated in a radio receiver.

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The preceding discussion has presented a mixer that provides programmable gain, reduces flicker-noise, and/or operates from small supply voltages. By employing the programmable gain RF transconductance section, a mixer includes programmable gain; by utilizing native transistors within the switching quad transistors, flicker-noise is reduced; and by utilizing a folded-cascoded common mode

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1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079 1080 1081 1082 1083 1084 1085 1086 1087 1088 1089 1090 1091 1092 1093 1094 1095 1096 1097 1098 1099 1100 1101 1102 1103 1104 1105 1106 1107 1108 1109 1110 1111 1112 1113 1114 1115 1116 1117 1118 1119 1120 1121 1122 1123 1124 1125 1126 1127 1128 1129 1130 1131 1132 1133 1134 1135 1136 1137 1138 1139 1140 1141 1142 1143 1144 1145 1146 1147 1148 1149 1150 1151 1152 1153 1154 1155 1156 1157 1158 1159 1160 1161 1162 1163 1164 1165 1166 1167 1168 1169 1170 1171 1172 1173 1174 1175 1176 1177 1178 1179 1180 1181 1182 1183 1184 1185 1186 1187 1188 1189 1190 1191 1192 1193 1194 1195 1196 1197 1198 1199 1200 1201 1202 1203 1204 1205 1206 1207 1208 1209 1210 1211 1212 1213 1214 1215 1216 1217 1218 1219 1220 1221 1222 1223 1224 1225 1226 1227 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245 1246 1247 1248 1249 1250 1251 1252 1253 1254 1255 1256 1257 1258 1259 1260 1261 1262 1263 1264 1265 1266 1267 1268 1269 1270 1271 1272 1273 1274 1275 1276 1277 1278 1279 1280 1281 1282 1283 1284 1285 1286 1287 1288 1289 1290 1291 1292 1293 1294 1295 1296 1297 1298 1299 1300 1301 1302 1303 1304 1305 1306 1307 1308 1309 1310 1311 1312 1313 1314 1315 1316 1317 1318 1319 1320 1321 1322 1323 1324 1325 1326 1327 1328 1329 1330 1331 1332 1333 1334 1335 1336 1337 1338 1339 1340 1341 1342 1343 1344 1345 1346 1347 1348 1349 1350 1351 1352 1353 1354 1355 1356 1357 1358 1359 1360 1361 1362 1363 1364 1365 1366 1367 1368 1369 1370 1371 1372 1373 1374 1375 1376 1377 1378 1379 1380 1381 1382 1383 1384 1385 1386 1387 1388 1389 1390 1391 1392 1393 1394 1395 1396 1397 1398 1399 1400 1401 1402 1403 1404 1405 1406 1407 1408 1409 1410 1411 1412 1413 1414 1415 1416 1417 1418 1419 1420 1421 1422 1423 1424 1425 1426 1427 1428 1429 1430 1431 1432 1433 1434 1435 1436 1437 1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448 1449 1450 1451 1452 1453 1454 1455 1456 1457 1458 1459 1460 1461 1462 1463 1464 1465 1466 1467 1468 1469 1470 1471 1472 1473 1474 1475 1476 1477 1478 1479 1480 1481 1482 1483 1484 1485 1486 1487 1488 1489 1490 1491 1492 1493 1494 1495 1496 1497 1498 1499 1500 1501 1502 1503 1504 1505 1506 1507 1508 1509 1510 1511 1512 1513 1514 1515 1516 1517 1518 1519 1520 1521 1522 1523 1524 1525 1526 1527 1528 1529 1530 1531 1532 1533 1534 1535 1536 1537 1538 1539 1540 1541 1542 1543 1544 1545 1546 1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573 1574 1575 1576 1577 1578 1579 1580 1581 1582 1583 1584 1585 1586 1587 1588 1589 1590 1591 1592 1593 1594 1595 1596 1597 1598 1599 1600 1601 1602 1603 1604 1605 1606 1607 1608 1609 1610 1611 1612 1613 1614 1615 1616 1617 1618 1619 1620 1621 1622 1623 1624 1625 1626 1627 1628 1629 1630 1631 1632 1633 1634 1635 1636 1637 1638 1639 1640 1641 1642 1643 1644 1645 1646 1647 1648 1649 1650 1651 1652 1653 1654 1655 1656 1657 1658 1659 1660 1661 1662 1663 1664 1665 1666 1667 1668 1669 1670 1671 1672 1673 1674 1675 1676 1677 1678 1679 1680 1681 1682 1683 1684 1685 1686 1687 1688 1689 1690 1691 1692 1693 1694 1695 1696 1697 1698 1699 1700 1701 1702 1703 1704 1705 1706 1707 1708 1709 1710 1711 1712 1713 1714 1715 1716 1717 1718 1719 1720 1721 1722 1723 1724 1725 1726 1727 1728 1729 1730 1731 1732 1733 1734 1735 1736 1737 1738 1739 1740 1741 1742 1743 1744 1745 1746 1747 1748 1749 1750 1751 1752 1753 1754 1755 1756 1757 1758 1759 1760 1761 1762 1763 1764 1765 1766 1767 1768 1769 1770 1771 1772 1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783 1784 1785 1786 1787 1788 1789 1790 1791 1792 1793 1794 1795 1796 1797 1798 1799 1800 1801 1802 1803 1804 1805 1806 1807 1808 1809 1810 1811 1812 1813 1814 1815 1816 1817 1818 1819 1820 1821 1822 1823 1824 1825 1826 1827 1828 1